New Technologies for Lifting Liquids from Natural Gas Wells

during the Period 05/15/2001 to 05/14/2002

By

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Colorado School of Mines

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Final Report

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Disclaimer

Abstract

When initially completed, many natural gas wells are capable of lifting liquids to the surface. But, with depletion of the reservoir pressure, there comes a time when liquids can no longer be lifted to the surface and they begin to accumulate in the bottom of the well, dramatically inhibiting or stopping gas production. The cause of diminished liquid-lifting ability is the decline of liquid droplet production at gas flow rates below the Turner-Hubbard-Dukler critical velocity.

In this research, three tasks were planned for developing technologies that enhance droplet production and facilitate lifting at low gas flow rates:

Task 1: Enhancing droplet production. To overcome the limitation of diminished capacity for droplet generation at the low gas velocities of stripper gas wells, develop devices that stimulate droplet production by sonic and ultrasonic means in bench-top and flow-loop tests.

Task 2: Integrated modeling of gas well production. Test and develop a numerical model that combines the complexities of two-phase flow in the wells and the adjacent reservoir with the droplet-stimulation technologies. Use this model to develop plans for field tests.

Task 3: Field testing of new technologies. Test the previously developed tubing-insert technology in a field setting.

Accomplishments for each of these tasks are summarized below.

Task 1: Enhancing droplet production. We expanded the scope of this task to include testing of rotational and two-fluid devices as well as vibrational (sonic and ultrasonic) devices for droplet production. Vibrational and two-fluid devices were obtained from commercial sources; we assembled a rotating device for testing. Bench-top tests showed that all three classes of devices could produce small droplets, but the ultrasonic devices produce the smallest droplets. The rate of conversion of bulk liquid to droplets is highest for the rotational and two-fluid devices.

The three classes of devices were also tested in a flow loop. The flow-loop tests showed that very small droplets (about 3 micron diameter droplets produced with an ultrasonic device) can be transported the height of the loop (10.7 m, or 35 feet) without coalescing on the walls of the tubing. Flow-loop tests with the rotational and two-fluid devices were discouraging. We were unable to produce small droplets with the rotational device in the confines of the 6.35-cm-ID (2.5-inch-ID) of the flow loop. And with the two-fluid device, 50 to 70% of the produced droplets impinged and coalesced on the ID of the flow loop within ten feet of the device. According to specifications for the two-fluid device, the produced droplets should have diameters between 20 and 90 microns.

Heuristics in the literature and conversations with experts on droplet transport led to the expectation that droplets with diameters less than 30 microns could be transported from the bottom of a well to the surface without significant difficulty.

An energy analysis showed that a barrel of water could be converted to 30-micron droplets for less than 30 cents.

Task 2: Integrated modeling of gas well production. We began simulation of the reservoir-well system with Eclipse 100 models. One model showed that incomplete removal of water from the well diminished ultimate gas recovery by about 20%.

Task 3: Field testing of new technologies. Progress on Task 3 was limited to preliminary discussions of suitable wells with operators.

Table of Contents

Description of Approaches

Task I: Enhancing droplet production. This laboratory effort consisted of two parts: bench-top tests, and flow-loop tests. We completed bench-top tests of vibrating, rotating, and two-fluid devices for stimulating droplet production. The goal of these tests was to identify promising approaches for making droplets of the desired size for further testing in the flow loop.

In tests for vibrational devices, a small quantity of water was vibrated with a sonic (less than 20,000 hz) or ultrasonic (greater than 20,000 hz) driver. Finding suitable devices for these tests was a chore. I pursued many leads on the internet and by telephone. In Table 1, I list the commercial sources of ultrasonic devices that were contacted. The vibrational drivers that were selected for testing consisted of a vibrational transducer that is available in the Mining Department at CSM, and piezo devices obtained from Radio Shack and APC International. The vibrational transducer in the Mining Department was suited for tests up to about 400 hz. The piezo device from Radio Shack operates at 3,000 hz and requires a 9-volt battery. APC International provides a wide variety of piezo devices, including bending disks with optimum frequencies up to about 10,000 hz, air transducers that operate at 24,000 and 42,000 hz, and ultrasonic humidification devices that operate at 1.6 Mhz. For testing of the sub-50,000 hz APC International devices, a frequency generator and an amplifier were used for providing the needed electrical excitation. The 1.6 Mhz device requires 48-volt AC power, which was provided by a variable voltage transformer. For droplet production tests at frequencies up to 3,000 hz, we measured the diameter of droplets from digital images.

Table 1. Commercial Sources of Ultrasonic Devices.

Company	Contacts	Products
APC International (americanpiezo.com)	Rich Brooks 570-726-6961	Distributes a variety of ultrasonic products – including the same transducer that DGH offers – but the APC price is about $14!
Branson	Jeff Hilgert 203-796-0461	Ultrasonic cleaners that operate at 20 to 40 kHz
Clomatic Corp	B. Y. Chen (clco5046@ms14.hinet.net)	Makes the transducer that is distributed by DGH Systems
DGH Systems	Scott Herr 717-293-5210	Distributes a low-cost ($40) transducer for humidification
Electrowave (electrowave.com)	Gary Lewis 715-426-7378 Mark Sellins 858-695-2227	Website speaks effusively about high power transducers that they make – rather than distribute for someone else.
Etrema	Tim Drake 816-246-0566 Duane Canny 515-296-8030	Makes some vibrational devices for down-hole seizmic stimulation. Specialize in magneto-strictive devices that usually operate at less than 20,000 hz.
Sono-Tek (sono-tek.com)	Dean Calamaras	Nozzles with frequencies from 25 to 120 kHz, and flow rates from 1 to 6 gal/hr

	845-795-2020 x127	
Sonics & Materials (sonicsandmaterials.com)	Ed Neeb 203-270-4600 x316 Mike Donatti	A competitor of Sono-Tek with roughly equivalent products at about half the price. Working on some down-hole devices for an undisclosed application.
Stulz (stulz-ats.com)		Use TDK transducers in products for humidification.
TDK (www.tdk.co.jp/tefe02/ef441_nb.pdf)		Piezo transducers: NB-514S-01-0, and NB-59S-09S-0 (These are very similar to those available from APC and DGH, but their cost is $50 to $100.) Magneto-strictive transducers: V2X series

We tested two different types of rotational devices: a Dremel tool with a 1-inch-diameter cutting disk attached, and a child's siren whistle. For tests with the Dremel tool, a stream of water was directed at the rapidly spinning cutting disk; for tests with the siren whistle, water was blown through the whistle with compressed air.

For tests of two-fluid nozzles, I first located liquid nebulizers that are used in the medical field for inhalation therapy (Hudson RCI No. 1882 Micro Mist Nebulizer; Omron No. 9911 AIRS Nebulizer). These nebulizers consist of small cups (about 5 ml capacity) concentrically mounted on an air nozzle. The liquid is sucked into the orifice region of the air nozzle where it breaks into small drops. An air supply of about 1 scf per minute is needed for the nebulizers. A large capacity two-fluid nozzle was purchased (Sonimist Model 900-2 from Misonix). Operation of this nozzle requires a gas stream of 15 to 20 SCF per minute combined with injection of bulk liquid at a variety of rates.

In addition to bench-top tests of droplet production, we conducted flow-loop tests to study the transport of droplets. The flow-loop lay-out is shown in Figure 1. A key feature of the flow loop is the droplet generator, which was adapted to each approach used to produce droplets. For tests with ultrasonic devices (just the 1.6 MHz ultrasonic transducers were tested in the flow loop), the configuration in Figure 2 was used. The ultrasonic device was located at the bottom of the flow loop in a shallow pool of water. For tests with the rotational devices (the Dremel tool), the configuration of Figure 3 was used. The rotational device was located 2 to 3 feet from the bottom of the flow loop; water was blown onto this device by the flowing air as it agitated a shallow pool of water at the bottom of the flow loop. In tests with two-fluid devices, two configurations for the droplet generator were used. The approach for tests with the medical nebulizers is shown in Figure 4. As in tests with the rotational device, water was blown onto the nebulizer cup from a shallow pool of water at the bottom of the flow loop while a small stream of air was injected to the cup to nebulize the water. In tests with the two-fluid nozzle from Misonix, water and air were injected to the nozzle as shown in Figure 5. In all tests, we detected transport of droplets by scattering of light from the He-Ne laser beam and by collection of water in the gas-liquid cyclone separator.

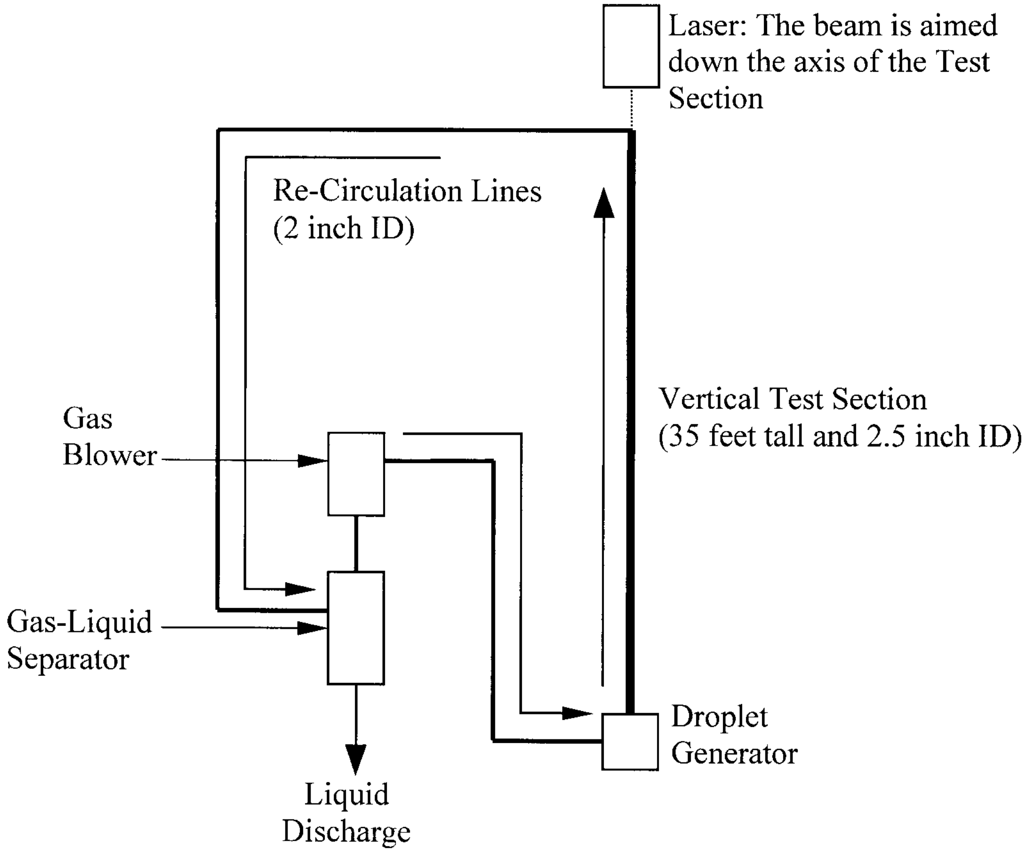

Figure 1. Schematic of Flow Loop.

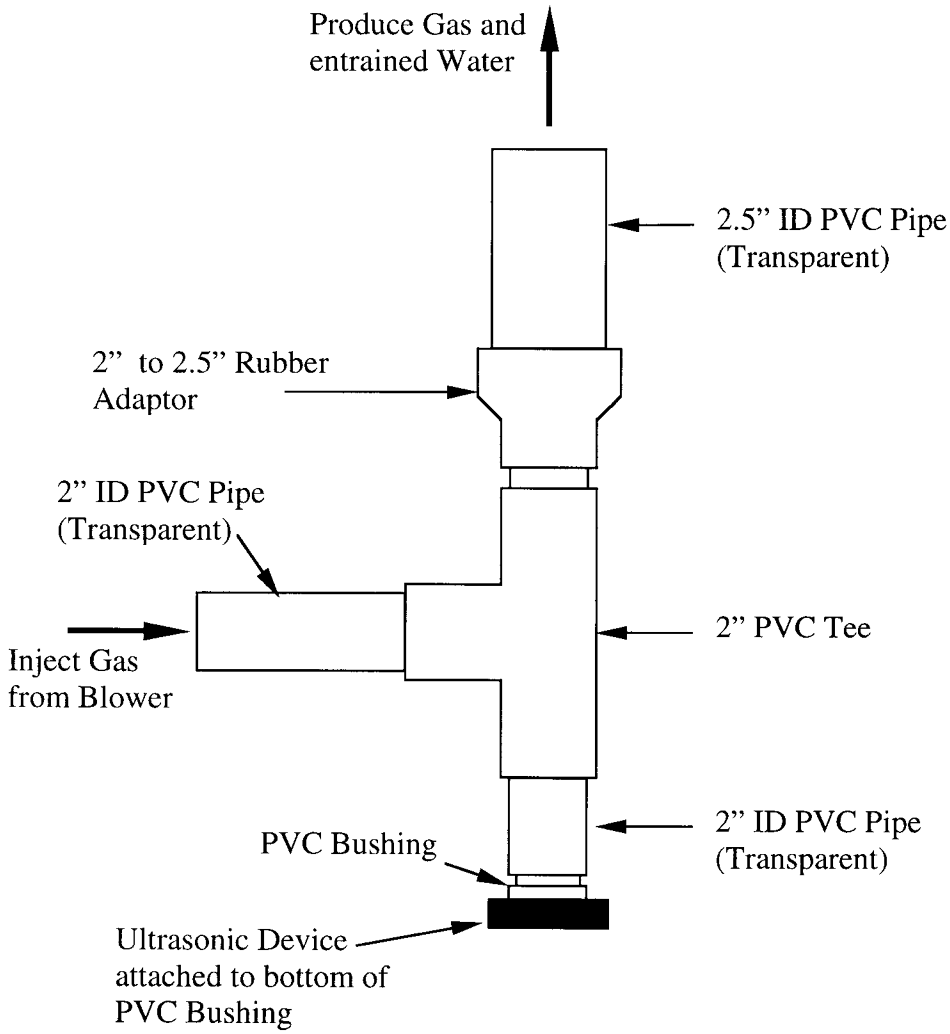

Figure 2. Schematic of the Droplet Generator for Tests with Ultrasonic Device.

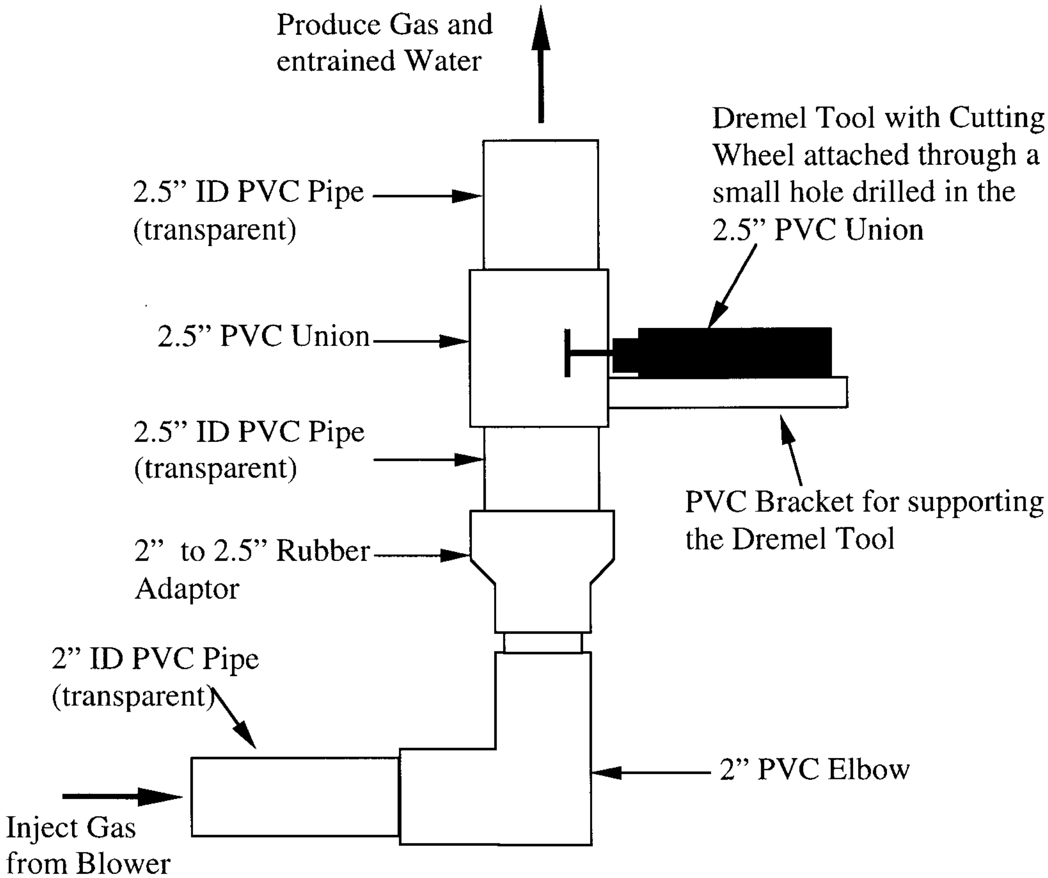

Figure 3. Schematic of the Droplet Generator for Tests with the Rotational Device.

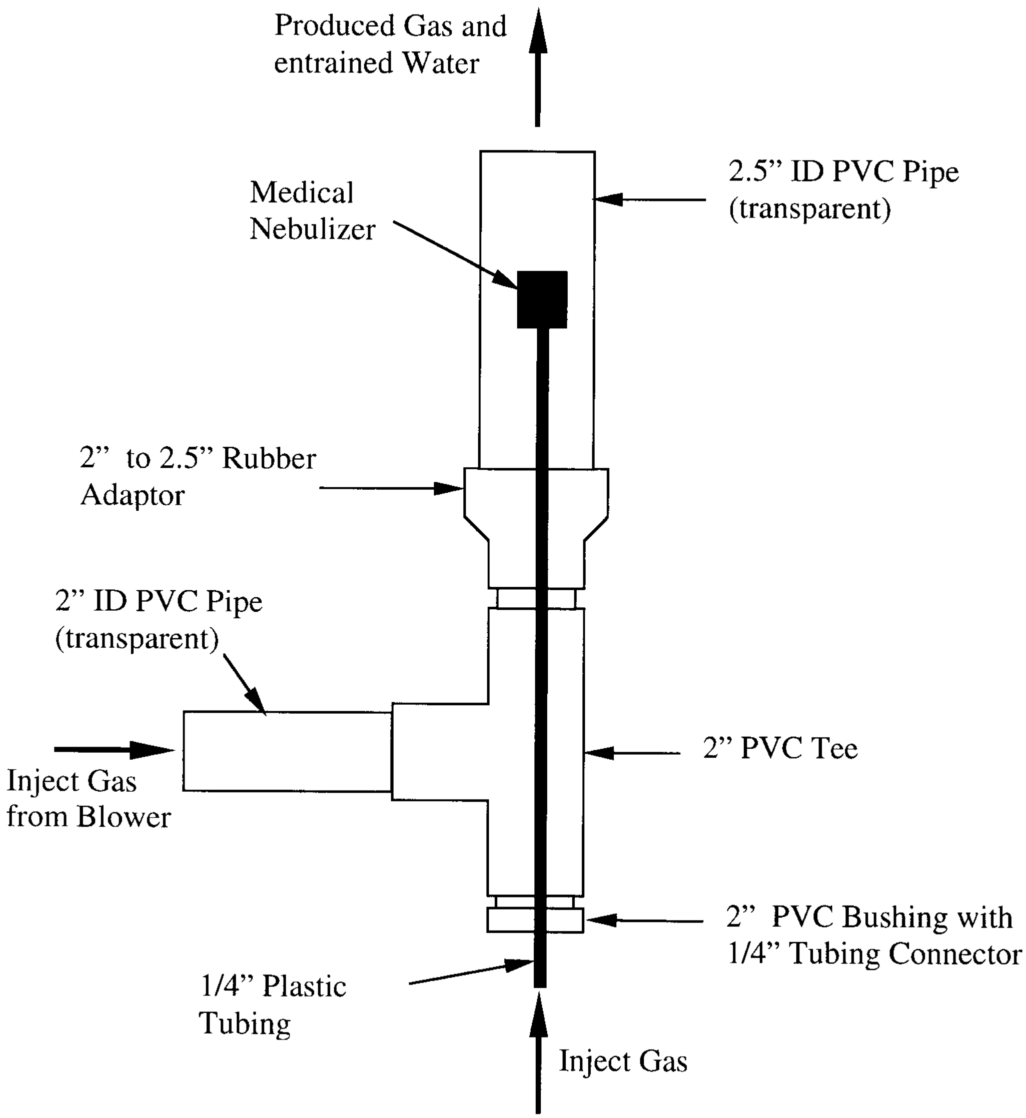

Figure 4. Schematic of the Droplet Generator for Tests with the Medical Nebulizer.

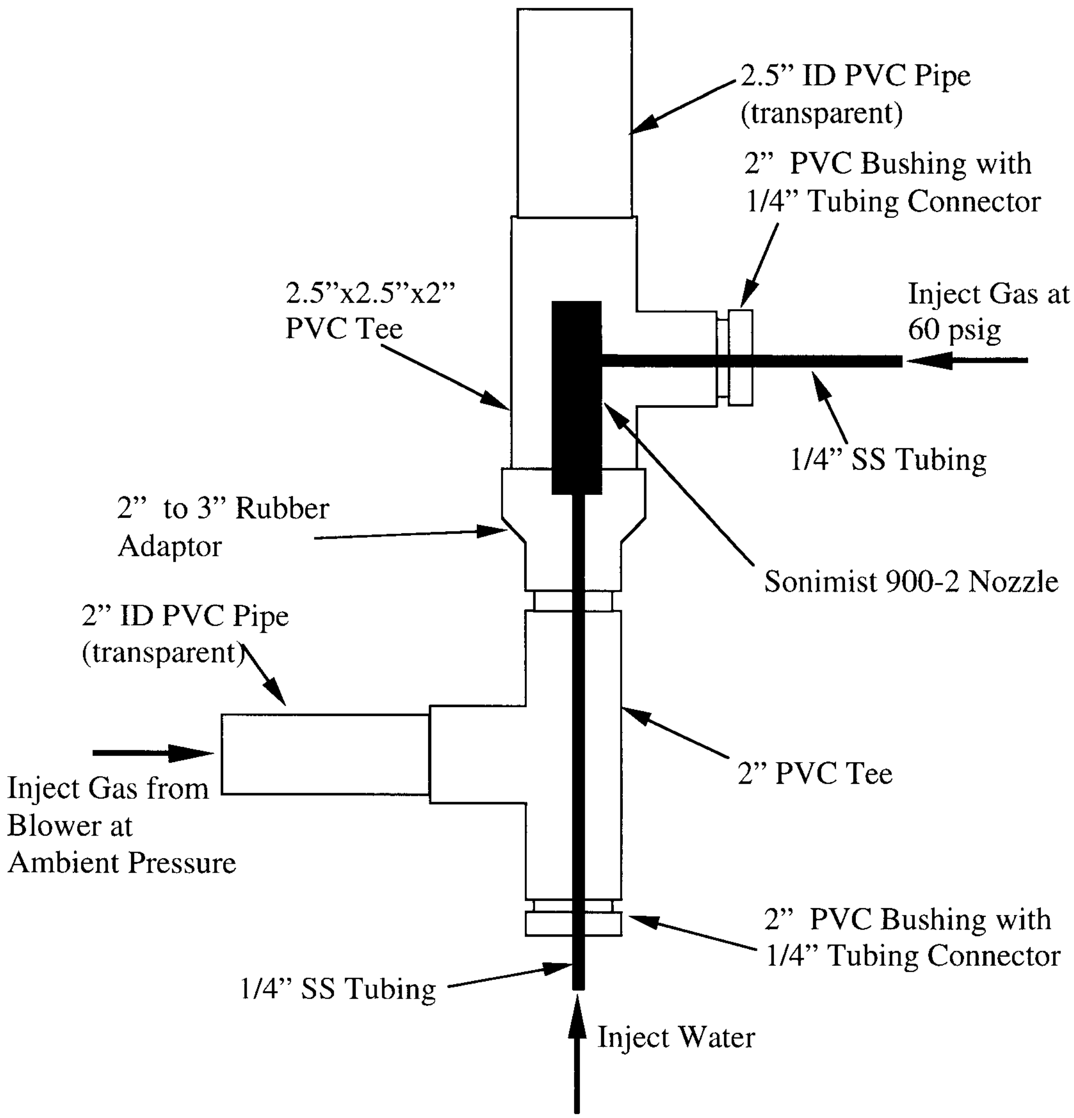

Figure 5. Schematic of the Droplet Generator for Tests with the Misonix Sonimist Nozzle (Model 900-2).

Task II: Integrated modeling of gas well production. In this task, we attempted to model the combined system that consists of the reservoir and the well. We hoped that this effort would increase our ability to plan and interpret field tests of lifting technology, as well as our understanding of the benefits of effective liquid lifting. Although we did not complete an integrated model, we did investigate separately the reservoir and well-bore issues with modeling. We developed several models of gas reservoirs using Eclipse 100. Again, these single-well models were not integrated models – they are just reservoir models. However, we adjusted the operation of the well to reflect problems that occur in gas reservoirs. Specifically, we converted the well from a gas producer to a water injector at regular time interval to simulate cessation of gas production and the consequent imbibition of water that should have accumulated in the well-bore. The amount of injected water is small – less than 10 barrels. Such small amounts of water could accumulate in the production tubing during normal gas production; when production ceases, it would fall to the bottom of the well where it can be imbibed by the producing formation.

I also wrote well-bore models in Excel Visual Basic using the Gray model and the Duns and Ros model as described by Brill and Mukherjee(1999). These models were used mostly to investigate operating conditions in wells that were considered in Task III.

Task III: Field testing of new technologies. For this task, I contacted a few producers with the hope of identifying wells for testing of the tubing-insert technology that we developed previously [Yamamoto and Christiansen (1999)]. A previous study [Putra (2000)] suggested the slug-flow regime was most suited for successful application of the tubing-inserts. Hence, after discussions with producers, I used the flow models from Task II to assess the flow conditions, including flow regimes, in the wells.

Results and Discussion

Task I: Enhancing droplet production. This section begins with discussion of the context of the problem of liquid lifting, continues with results of our research, and ends with discussion of feasible approaches for application of the results.

The root of the liquid-lifting problem in gas wells is droplet size. At high gas flow rates, liquids break into droplets of sufficiently small size for lifting by the gas. With decreasing gas flow rate, both the droplet creating capacity and the droplet lifting capacity decrease. This idea was succinctly represented by Turner, Hubbard, and Dukler (1969) in their expression for critical gas velocity v_c – the minimum velocity for dispersing and lifting liquid as droplets:

$$v_c = 0.567\left[\frac{(\rho_l - \rho_g)\sigma_{gl}}{\rho_g^{\ 2}}\right]^{1/4} \qquad 1$$

Here, the critical velocity has units of ft/sec, the liquid density ρ_l and the gas density ρ_g have units of g/cm^3, the gas-liquid interfacial tension σ_{lg} has units of dyne/cm. If the velocity of gas declines below v_c, then liquid accumulation begins. For a natural gas-water system at 311 K and 689 kPa (100°F and 100 psia), the critical velocity is about 6.7 m/sec (22 ft/sec).

In this research, we sought ways to stimulate production of droplets that can be lifted by velocities less than the critical velocity of Eq. 1. To understand the target better, let's estimate the size of droplets at the critical velocity using the critical Weber number:

$$N_{We,c} = \frac{\rho_g d v_c^{\ 2}}{\sigma_{gl}} \qquad 2$$

Turner *et al.* used 30 for the value of the critical Weber number; however, a range of 10 to 30 might be more appropriate. Then, the range of average diameter of droplets at the critical velocity can be estimated from Eq. 2:

$$10\frac{\sigma_{gl}}{\rho_g v_c^{\ 2}} < d < 30\frac{\sigma_{gl}}{\rho_g v_c^{\ 2}} \qquad 3$$

For the gas-water system at 311 K and 689 kPa (100°F and 100 psia), the effective diameter d is between 3 and 8 mm.

To produce smaller droplets that will provide for liquid lifting at lower gas flow rates, we investigated three approaches for droplet production: vibrational, rotational, and two-fluid flow. There are correlations in the literature for estimating the size of droplets produced with each of these approaches [Bayvel and Orzechowski(1993), Liu(2000), and Masters(1979)]. Here, we focus on a correlation for the vibrational approach because it showed the most promise for future development – and because it is the easiest to understand and use. According to Lang(1962), the size of droplets produced by sound can be estimated with the following expression:

$$d = 0.34\left(\frac{8\pi\sigma_{gl}}{\rho_l f^2}\right)^{1/3} \qquad 4$$

In this expression, d is the droplet diameter(m or cm), σ_{gl} is the gas-liquid interfacial tension(mN/m or dyne/cm), ρ_l is the density of the liquid(kg/ cm^3 or g/cm^3), and f is the sound frequency (Hz or cycles per second). Lang based the correlation of Eq. 4 on measurements at frequencies of 7,000 to 1,000,000 Hz.

During the second quarter of this project, we measured the size of droplets produced in vibrational tests for frequencies from 25 to 3000 Hz. Digital images of droplets formed in tests with the vibrational transducer in the Mining Department are shown in Figures 6 to 9. In these tests, a shallow pool of water in a plastic cup was attached to the top of the transducer. Sizes of several droplets from each image were measured and averaged. The results of these measurements are predicted quantitatively by extending the Lang correlation to low frequencies as shown in Figure 10. The trend of decreasing droplet size with increasing frequency is easily seen in these figures.

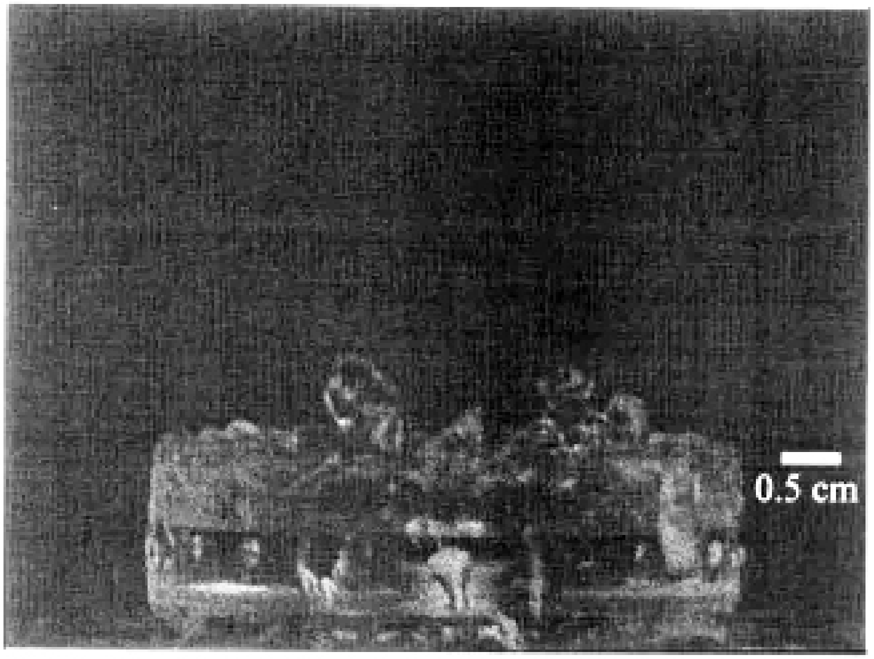

Figure 6. Droplet formation at 25 hz.

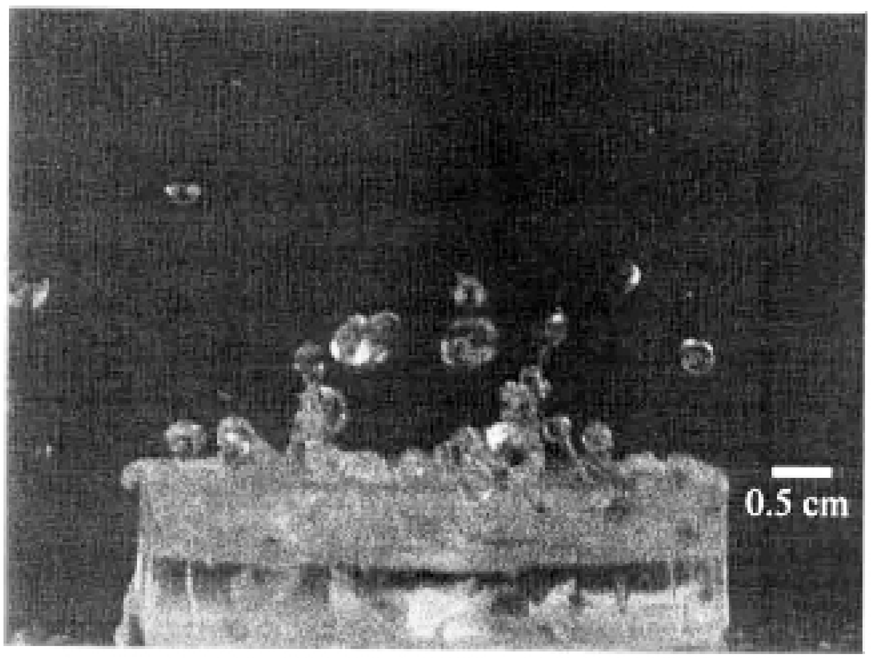

Figure 7. Droplet formation at 50 hz.

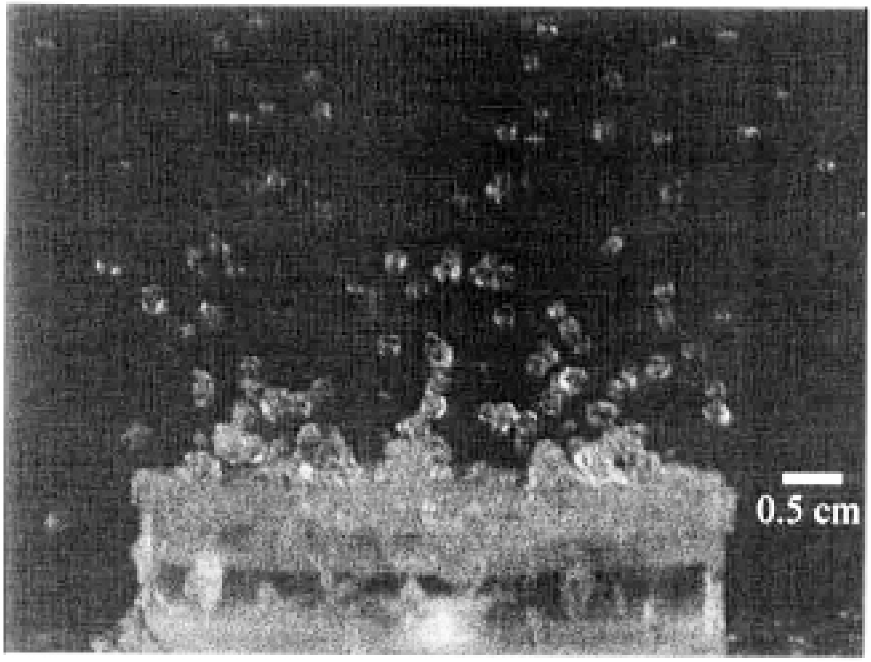

Figure 8. Droplet formation at 100 hz.

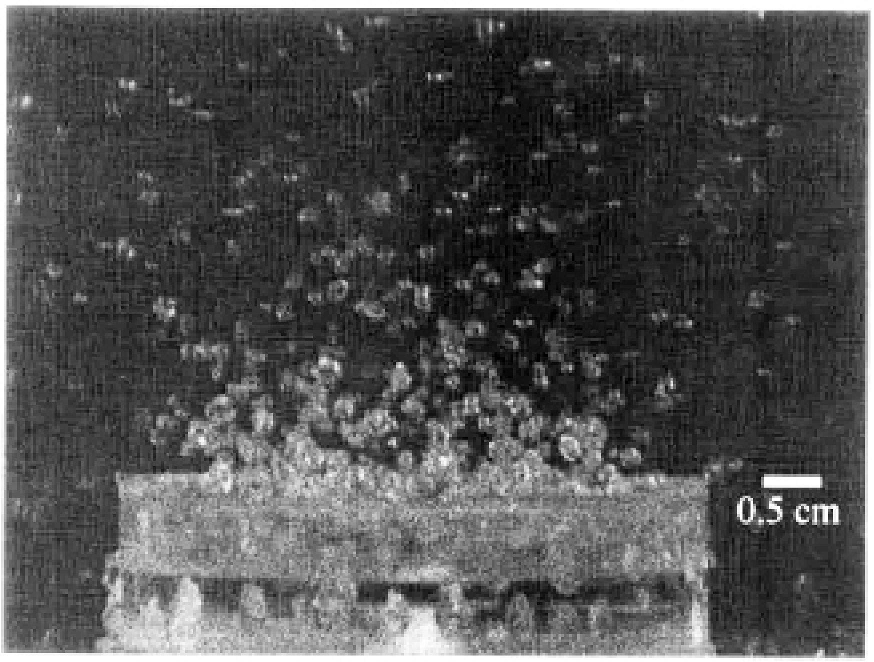

Figure 9. Droplet formation at 200 hz.

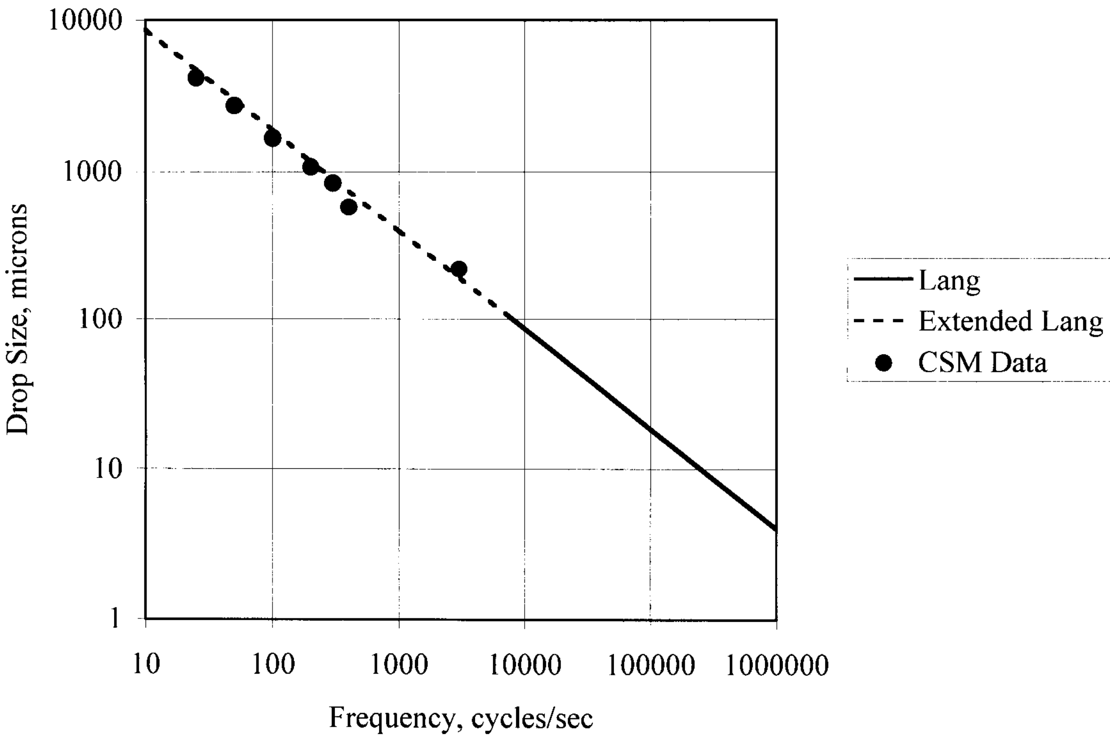

Figure 10. Extrapolating Lang's correlation to low frequencies quantitatively predicts our bench-top measurements.

The size of droplets produced by rotational devices decrease with speed of rotation and with diameter of the spinning wheel from which the liquid is released. Rotational devices are used in many spray-drying applications. In these applications the spinning wheel may be 6 to 10 inches in diameter. And the spray from the spinning wheel typically extends for many diameters beyond the wheel. Such dimensions are not suited to bottom-hole application where inside diameters of tubing and casing are generally less than 3 and 6 inches respectively. Our observations for 1-inch-diameter cutting wheels on Dremel tools spinning at 10,000 to 20,000 rpm conform to the descriptions in spray-drying texts [Masters, 1979]. The spray from the wheel extended 10 to 12 inches away from the wheel, and droplets of a wide size distribution were produced – we did not quantify the size distribution.

The size of droplets produced with two-fluid nozzles decreases with increasing gas flow rate and with decreasing liquid flow rate. With medical nebulizers, droplets with diameters less than 10 microns are produced for inhalation therapy. In these applications, just small quantities of liquid medication are applied at a low rate, usually just a few milli-liters per hour. Larger two-fluid nozzles are capable of much higher liquid rates – equivalent to ten or more barrels per day. (1 barrel per day is about the same as 100 ml per minute.) The dimensions of two-fluid nozzles and the associated plume of droplets are more compatible with bottom-hole dimensions than rotating devices. In bench-top tests with medical nebulizers the plumes were generally less than 2 inches in diameter after travel 3 feet from the nozzle. For the Misonix Sonimist two-fluid nozzle, the plume expanded to about 6 inches after traveling 3 feet from the nozzle. Droplet sizes for the Sonimist 900-2 nozzle are not available from Misonix. Data for the Sonimist 900-4 nozzle show droplet sizes in the 20 to 90 micron range.

Our bench-top tests and the literature convinced us that droplets of any desired size for liquid lifting can be produced with the appropriate choice of approach and operating conditions. After reaching this conclusion, we needed to answer the next big question: How far can we transport the droplets produced by one of these approaches in a well-bore? Answers to this question were obtained from flow-loop tests, from the literature, and from discussions with experts.

For flow-loop tests on the vibration approach for droplet production, we chose to use the ultrasonic transducer that operates at 1.6 Mhz. As described previously, this device was attached to the bottom of the flow loop with the face of the piezo disk at the bottom of a 1 to 2-inch-deep pool of water. When operating, the device should provide droplets with average diameter of about 3 microns at a liquid rate of 500 cm^3 per hour. Lifting of the 3-micron droplets to the top of the loop was readily observed by scattering of the laser beam by the droplets. Even with the flow rate at zero, the droplets remain suspended in the loop for more than 10 minutes. These results are very satisfying, probably even better than is needed in field applications. It is expected that the liquid-flow rate-capacity of ultrasonic devices increases with decreasing frequency. So devices operating at 100,000 hz that produce droplets in the 10 to 20 micron range might be very satisfactory. Such devices are commercially available, but they are much more expensive than the 1.6 Mhz transducer. Design of ultrasonic devices for specific application to gas wells is an issue that should be explored, but it is beyond the scope of this project.

Flow-loop tests with a rotational device (a Dremel tool with a 1-inch-diameter cut-off wheel) and with a two-fluid nozzle (medical nebulizers) were discouraging. In these tests, the device was located about 3 feet above the bottom of the flow loop. Water from the bottom of the flow loop was entrained in the flowing gas stream and carried to the vicinity of the generators. We were unable to detect any increase in liquid lifting due to the action of the generators. In the case of the rotational device, we hypothesize that the water is not being directed very effectively at the cutting wheel; as a result, the quantity of produced droplets is small. Furthermore, most if not all of the produced droplets probably impinge on the inside wall of the tubing.

For the two-fluid category of approaches to droplet production, we tested both the medical nebulizers and the Misonix Sonimist 900-2 nozzle in the flow loop. Results with the medical nebulizers were no better than the results for the rotational device described above. For the Misonix nozzle, the results were much more encouraging. Approximately one-third of the water injected to the nozzle was carried to the top of the 35-foot-tall flow loop and then to the liquid collection point shown in Figure 1. This result is consistent with the heuristics for lifting droplets of different sizes. It is suggested in the following paragraph that droplets larger than 30 microns are difficult to transport. I expect that a large portion of the droplets produced by the Sonimist nozzle are larger than 30 microns.

During the second quarter of this project, we found some insight for droplet transport in the literature on separation of suspended liquids from gas streams, as summarized by Fair *et al.* Figure 11 (Figure 18-133 of Fair *et al.*) shows typical classifications and separation equipment for separating particles from gases. We expect that the size range of most interest for the current research is 10 to 1000 microns. Particles with diameters of 1000 microns are quite easily removed from gases by gravitational settling. But in the range of 10 to 100 microns, more "aggressive" methods are needed, such as centrifugal separators or mist eliminators (impingement separators). By crude analogy, we expect that droplets in the 10 to 100 micron range will be more easily transported in the wells than the larger droplets. In the third quarter, I located Dr. Chien Pei Mao of Delavan Corporation who is an expert on droplet transport. He advised that droplets with diameters less than 30 microns are easily transported.

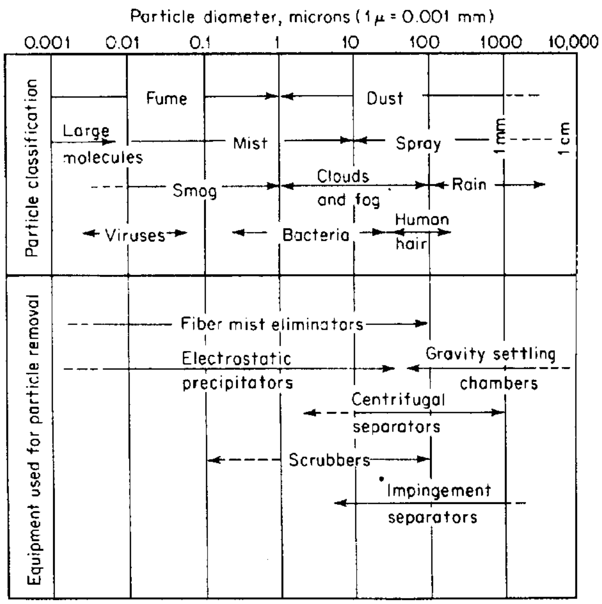

Figure 11. Particle nomenclature and separation schemes from Fair *et al.*

Another issue that we have addressed during this project is the cost of droplet production. Table 2 summarizes a theoretical analysis of the amount of energy needed to convert one barrel of water into 30-micron droplets. In the table, the volume and surface area of each droplet is first calculated. Next, the number of droplets with total volume of one barrel and their cumulative surface area is calculated. Finally, based on the surface energy per unit area of water, the required energy to make the droplets is obtained. (Surface area per unit area is equivalent to surface tension.) The end results, 2.11 Btu or 0.00062 kw-hr, is extraordinarily small. However, we have found in tests and the literature [Fair et al., 1973] that the actual energy requirement for droplet production is 1,000 to 10,000 times greater than the theoretical estimate of Table 2. Droplet production is surprisingly inefficient! Multiplying the theoretical requirement by 1,000, the required amount of energy is 0.62 kw-hr, which is equivalent to 3 cents if electrical power costs 5 cents per kw-hr. Using a multiplier of 10,000, the corresponding energy cost is 30 cents. The cost for making droplets should depend on the method used to make the droplets, whether vibrational, rotational, or two-fluid. But I have little additional information for distinguishing costs for the three approaches. For two-fluid nozzles, the estimated energy cost is about 90 cents per barrel based on operating dating from the catalog of Spraying Systems, Inc. This result for two-fluid nozzles is surprising because I had understood that two-fluid nozzles should be more efficient than other approaches.

Table 2. Energy Analysis for Droplet Production

30	Diameter, microns
1.41E-08	Volume of droplet, cm3
2.83E-05	Area of droplet, cm2
1.12E+13	Droplets per barrel
3.18E+08	Area of droplets per barrel, cm2
70	Surface energy for water, erg/cm2
2.23E+10	Energy, erg
2.11	Energy, btu
0.00062	Energy, kw-hr

Considering all of the above results, we have reached some useful conclusions for field application of droplet enhancing technologies. First, it is very unlikely that rotational devices can perform suitably for field application. Second, although two-fluid devices show more promise than rotational devices, we have not found a two-fluid device that is good enough for field testing – perhaps future studies will reveal a better two-fluid device. Third, vibrational devices do show some promise for successful field application. For vibrational devices, we suggest two alternative approaches for field testing:

1. Install the 1.6 Mhz transducers that are available from APC International in multiple tubing joints. These transducers cost about $15 each. Each transducer is capable of processing about 500 ml/hr to droplets between 1 and 5 microns. With 20 of the transducers installed at tubing joints, the total liquid capacity would be between 1 and 2 bbl/day. The devices require a 48-volt AC power supply.

2. Install one of the ultrasonic nozzles produced by Sono-Tek or Sonics & Materials. These nozzles are capable of processing up to 5 gal/hr (about 3 bbl/day), depending on the desired droplet size. The cost of a single Sono-Tek nozzle is $2500 plus $3500 for a power supply (quantity discounts are available). A higher capacity nozzle may be available later this year from Sono-Tek. Comparable nozzles from Sonics & Materials cost between $2000 and $3000.

The two approaches provide hope for a successful (technically and economically) field test.

Task II: Integrated modeling of gas well production. For this task, I hoped to combine a model of reservoir behavior with a model of well-bore behavior. While this may be possible, I was not able to accomplish it within the time frame of this project. I was able, however, to complete some analysis of the two separate problems.

First, we wrote Eclipse 100 models to simulate the effects of water accumulation on gas production. One of the Eclipse 100 models is a radial model with horizontal permeability of 10 md, and vertical permeability of 1 md. The model is 60 feet thick. Cumulative production and production rate are shown in Figures 12 and 13 for a period of about 2200 days. Figure 12 shows that the cumulative production for periodic shut-in with re-injection of a small amount of water is about 20% less than that for continuous production of gas. Figure 13 shows the corresponding variations in gas production rate. After injecting water during the shut-in period, the gas production rate slowly rises toward the rate that is found for the continuous production model. Clearly, water that is not removed from the well has a significant detrimental effect on ultimate gas recovery.

Second, I wrote Excel Visual Basic modules for well-bore simulation with the Gray model and the Duns and Ros model for two-phase vertical flow. I tested these models against performance in our flow loop. These models provided a lot of insight for interpretation of well-bore behavior, but there is much room for improvement. For example, many engineers in the industry maintain that a modified Hagedorn-Brown model is best for representing well-bore behavior. Other engineers favor mechanistic models. I used the Gray model primarily because it was very easy to write. I chose the Duns-Ros model because of its foundation in laboratory data and because it provides a fairly comprehensive capability for well-bore modeling – it can represent bubble flow, slug flow, the transition from slug flow to annular mist flow, and annular mist flow regimes.

Task III: Field testing of new technologies. For this task, the desire was to find some wells in which we could test the tubing-insert technology that we developed previously [Yamamoto and Christiansen (1999)]. Expecting that the slug-flow regime was most suited for successful application of the tubing-inserts[Putra (2000)], we used flow modeling software (developed in Task II) to assess the dominant flow regimes in wells suggested by various producers. Hence, after discussions with producers, I used the flow models from Task II to assess the flow conditions, including flow regimes, in the wells. Many of the wells that were offered were not dominated by the slug-flow regime. Hence there was little opportunity for pursuing this Task.

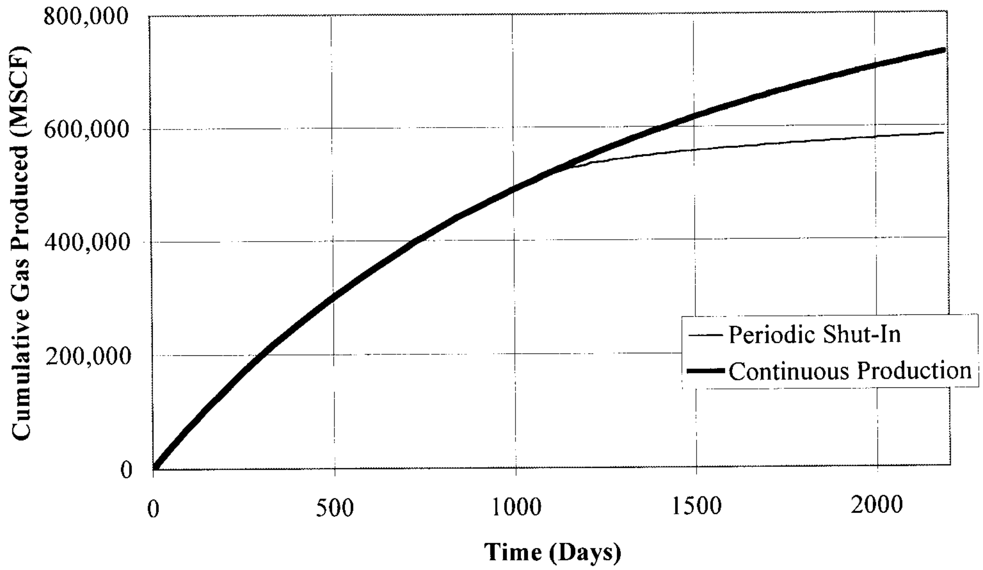

Figure 12. Cumulative production history for continuous production and for production with intermittent shut-in with water injection.

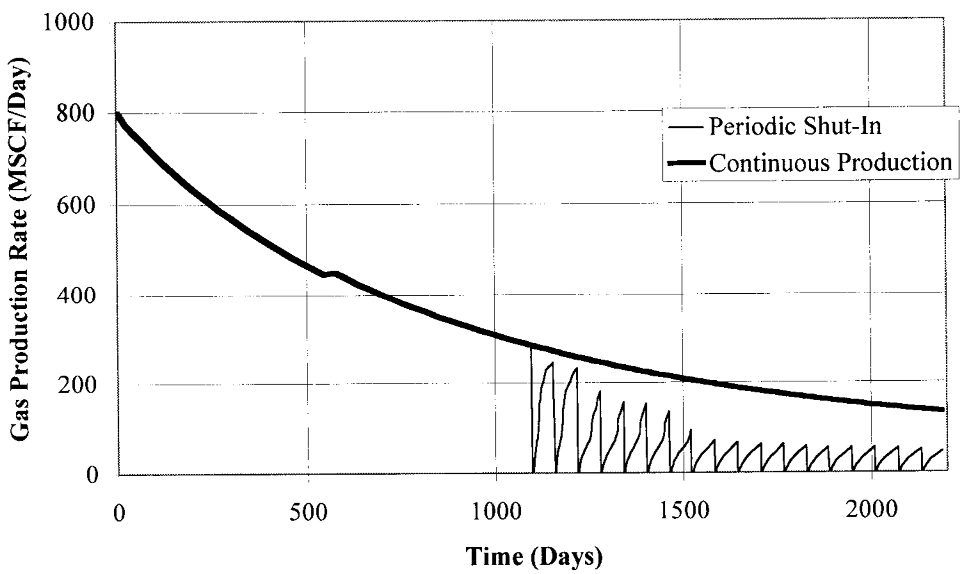

Figure 13. Production-rate history for continuous production and for production with intermittent shut-in with water injection.

Conclusions

1. Droplets in gas wells at the critical gas velocity have maximum equivalent diameters of 3 to 8 mm according to analysis that is consistent with the model proposed by Turner *et al.*(1969).
2. Bench-top tests and analysis show that production of small droplets is possible with vibrational, rotational, and two-fluid devices. The Lang(1962) correlation quantitatively predicts the average size of droplets produced by vibrational means for frequencies from 20 Hz to 1 MHz.
3. Flow loop tests with 1.6 MHz ultrasonic transducers showed that 3-micron droplets can be transported a long vertical distance. Literature on separating liquid droplets from gas streams support this observation. We expect that droplets up to 30-microns can be transported to the surface. Flow loop tests with rotational devices failed completely. Flow loop tests with two-fluid devices were moderately successful.
4. The estimated energy costs of droplet production are low per stage: 3 to 30 cents/bbl for production of 30-micron droplets. If the droplets are less than 30 microns in diameter, just one stage may be sufficient. For larger droplets, multiple stages will be needed in a typical gas well.
5. Feasible approaches for application of vibrational droplet generators have been developed.
6. Simulation results show that production from gas reservoirs can be significantly diminished by incomplete removal of water.

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